(54) Title: COMPENSATION FOR POLARIZATION-MODE DISPERSION IN MULTIPLE WAVELENGTH-DIVISION MULTIPLEXED CHANNELS

(57) Abstract: Techniques for compensating for polarization-mode dispension (PMD) in multiple wavelength-division multiplexed (WDM) channels (102) by processing all WDM channels in the same manner without demultiplexing the channels. A feedback control (136) is provided to decrease the worst-case power penalty and the channel fading probability by optimizing over the entire group of WDM channels.

NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) **Designated States** *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

COMPENSATION FOR POLARIZATION-MODE DISPERSION IN MULTIPLE WAVELENGTH-DIVISION MULTIPLEXED CHANNELS

[0001]   This application claims the benefit of U.S.

5   Provisional Application No.60/187,126, filed on March 6,

2000.

Background

[0002]   This application relates to compensation for

optical dispersion, and more specifically, to techniques

10   for reducing polarization-mode dispersion in optical

media such as optical fiber links in optical wavelength-

division multiplexing (WDM) systems.

[0003]   Some optical transmission media such as optical

fibers are birefringent and hence exhibit different

15   refractive indices for light with different polarizations

along two orthogonal principal directions. Therefore, an

optical signal, that comprises two components along the

two orthogonal principal directions for each frequency,

can be distorted after propagation through the

20   transmission medium since the two components propagate in

different group velocities. This optical dispersion is

generally referred to as polarization-mode dispersion

("PMD").

[0004]   The degree of PMD may be approximately characterized by the average differential group delay ("DGD") between two principal states of polarization. Typical causes for such birefringence in fibers include,

5   among others, imperfect circular core and unbalanced stress in a fiber along different transverse directions. The axis of birefringence of the optical fiber can change randomly on a time scale that varies between milliseconds and hours, depending on the external conditions. Thus,

10   the DGD in an actual PMD fiber is not a fixed value but a random variable that has a Maxwellian probability density function.

[0005]   Such polarization-mode dispersion is undesirable in part because the pulse broadening can

15   limit the transmission bit rate, the transmission bandwidth, and other performance factors of an optical communication system. In fact, PMD is one of key limitations to the performance of some high-speed optical fiber communication systems at or above 10 Gbits/s per

20   channel due to the fiber birefringence. Fibers with significant PMD (e.g., about 1 to 10 ps/km$^{1/2}$) are used in various fiber networks, particularly in those that were deployed in 1980's and early 1990's.

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Summary

[0006]   The present disclosure includes PMD compensation in WDM systems without wavelength demultiplexing. All WDM channels are guided through the

5   same optical path in a PMD compensation module. The overall system performance can be improved by reducing the fading probability for one or more worst-performing channels at any given time.

[0007]   One embodiment of a PMD compensation system

10   includes a PMD compensator and a feedback control that produces a control signal for controlling the PMD compensator. The PMD compensator guides a plurality of WDM optical channels through a common optical path to modify a differential group delay (DGD) in each channel.

15   The PMD compensator is operable to adjust the DGD in response to the control signal. The feedback control is coupled to measure a property of the channels as a whole and operable to generate the control signal according to the measured property.

20

Brief Description of the Drawings

[0008]   FIG. 1 shows a PMD compensation system based on one embodiment.

[0009]   FIG. 2A shows simulation results of the power penalty through the system in FIG. 1.

[0010]   FIG. 2B shows the Maxwellian probability distribution for the differential group delay (DGD) in the input signal.

[0011]   FIGS. 3A, 3B, and 4 show measured power penalty and eye diagram for four WDM channels with and without using a PMD compensation system based on the design in FIG. 1.

[0012]   FIG. 5 compares the simulated probability density function for the channel with the worst DGD with and without the PMD compensation.

[0013]   FIG. 6 shows another PMD compensation system with two or more adjustable PMD compensators.

Detailed Description

[0014]   The techniques for PMD compensation described in this disclosure are in part based on the recognition that, the high DGD values in the distribution tail of the DGD Maxwellian probability density function may have significant and adverse impact on the signal degradation even though the probabilities for such high DGD values to

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occur are low. Hence, it is desirable to design a PMD

compensation scheme capable of reducing the impact of

such high DGD values with low probabilities. In

addition, as an alternative to compensation for the PMD

5   in each individual WDM channel, the overall effects of

PMD on multiple WDM channels may be reduced by processing

the multiple WDM channels as a whole. This compensation

scheme may be used to reduce the device complexity and

cost for the PMD compensation.

10   [0015]   In principle, an ideal multiple-channel first-

order PMD compensator would generate PMD vectors opposite

to the PMD vectors of the transmission fiber at each

channel wavelength. In the low-PMD regime where the

average DGD in the transmission link is low, the

15   correlation bandwidth of PMD vectors for different WDM

channels is approximately inversely proportional to the

amplitude of the PMD vector and is greater than the

channel spacing. Hence, the PMD vectors on the Poincaré

sphere for different WDM channels are correlated. Under

20   this condition, different WDM channels may be treated

equally in an appropriate PMD compensation scheme to

effectively compensate for the PMD in different WDM

channels at the same time.

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[0016]   In the high-PMD regime where the correlation bandwidth of the PMD vectors is less than the WDM channel spacing, however, the PMD vectors of different WDM channels are independent from one another. Therefore,

5   under the conventional wisdom, this appears to suggest that different WDM channels should be separately compensated. Some PMD compensation schemes follow this rational by using a WDM demultiplexer to first separate the different WDM channels and then using separate PMD

10   compensators to respectively compensate for the PMD in different WDM channels. The PMD-compensated channels are then combined by a WDM multiplexer at the output. Such schemes may increase both structural complexity and the cost of the PMD compensation system.

15   [0017]   The present disclosure goes beyond the conventional wisdom to teach that, different WDM channels may still be treated equally as a whole even in the high-PMD regime where the correlation bandwidth of the PMD vectors is less than the WDM channel spacing. This is in

20   part based on the recognition that two or more WDM channels are not likely to be severely degraded by the PMD at any given time. Instead, statistically, the majority of the WDM channels at any given time are likely to be in the low-DGD regime. Techniques of this

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disclosure use one or more PMD compensators to equally process different WDM channels without channel discrimination by guiding each and every WDM channels through the same optical path. This approach can

5 significantly decrease the worst-case power penalty and the channel fading probability by optimizing over the entire group of WDM channels although each WDM channel may still have some residue PMD.

[0018] In particular, a feedback control mechanism is

10 used to monitor the degree of PMD degradation on the overall performance of the combined WDM channels by measuring a property of the combined WDM channels. Based this monitoring, the feedback control mechanism dynamically adjusts the one or more PMD compensators to

15 reduce the PMD effect on the overall performance of the combined WDM channels.

[0019] FIG. 1 shows one embodiment of a PMD compensation system 100. A fiber 101 is used to transport an input optical signal 102 with multiple WDM

20 channels from an optical link with PMD. A PMD compensator 110 is coupled in the fiber 101 to receive and process the input optical signal 102 to produce a PMD-compensated signal 116. Notably, the PMD compensator 110 is designed to process the input signal 102 as a

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whole without distinguishing individual WDM channels.
Hence, different WDM channels are not demultiplexed and
separated within the PMD compensator 110 but are guided
through the same optical path within the PMD compensator
5   110.

[0020]   In the illustrated implementation, the PMD
compensator 110 includes a polarization controller 112
and a polarization-maintaining (PM) fiber 114. The
polarization controller 112 controls and adjusts the
10   polarization of light so that its output signal has a
particular polarization. In particular, the polarization
controller 112 is operable to set its output polarization
in any desired polarization state and may operate in
response to an external control signal. Several
15   implementations of such a polarization controller are
well known. The PM fiber 114 is birefringent and has
fixed orthogonal principal polarization axes. Hence, as
the polarization controller 112 rotates the polarization
of the input signal 102 relative to the principal
20   polarization axes of the PM fiber 114, a delay between
the two orthogonal polarizations can be introduced
through propagation through the PM fiber 114 in each WDM
channel.

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[0021]   The system 100 implements an optical coupler

120 in the fiber 101 to tap a small PMD monitor signal

122 from the signal 116. The remaining portion of the

signal 116 is then sent out in the fiber 101 as the

5   output signal 124. A PMD feedback control loop 130 is

used to receive and process the PMD monitor signal 122

and to produce a control signal 136A for controlling the

PMD compensator 110. In the example shown, the control

signal 136A is used to control the operation of the

10   polarization controller 112. This PMD feedback control

loop 130 measures the degree of the total degradation of

the combined WDM channels in the signal 116 at any given

moment, and adjusts the amount of DGD it produces in the

signal 116 to optimally decrease the DGD for the worst

15   WDM channel. Hence, although each channel may have some

residual PMD degradation, the probability of any of the

channels being severely degraded by PMD can be

significantly reduced. This technique may be used to

significantly reduce the power-penalty distribution tail

20   for each WDM channel and the probability of link outage.

[0022]   One realization of the PMD feedback control

loop 130 includes a single optical detector 132, a RF

power detector 134, and a feedback control circuit 136.

The optical detector 132 may be a high-speed detector

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capable of responding at the highest bit rate in the WDM

channels to convert the optical monitor signal 122 into

an electrical detector signal 132A. The detector signal

132A essentially replicates the optical modulations in

5   the total optical power of the combined WDM channels in

form of a modulated current or voltage. The RF power

detector 134 receives the detector signal 132A and

measures the electrical power associated with the signal

132A which is proportional to the square of the modulated

10   current or voltage in the signal 132A. The RF power

detector 134 then produces a signal 134A that is

proportional to the measured AC electrical power of the

detector signal 132A either in the entire frequency range

or a selected frequency range. Note that the DC portion

15   of the measured electrical power could be removed by

filtering 134. This signal 134A is then processed by the

feedback control circuit 136 to produce the control

signal 136A. This signal 136A is fed back to the

polarization controller 112 to increase the detected RF

20   power by adjusting the polarization of the PMD

compensator 110. This feedback operation can improve or

optimize the overall system performance and produce

increased eye-openings for the WDM data streams in the

output 124.

[0023]   The RF power detector 134 may include one or more RF bandpass filters to filter the power signal in one or more frequency bands to generate one or more signals like the signal 134A. This technique could be used to increase the sensitivity of the feedback control to the PMD-induced signal variations in the input WDM channels because the power variation in the signal 134A in a particular frequency band may be more sensitive than power variations in other frequency bands. Alternatively, a tunable RF bandpass filter may be used in the power detector 134 to adjust the frequency band of the signal 134A to optimize the detection sensitivity. The feedback control circuit 136 selects one signal 134A or a combination of these signals that is most sensitive to the PMD variation to produce the control signal 136A.

[0024]   FIG. 2A shows simulation results of the power penalty corresponding to different DGD values. FIG. 2B shows the corresponding Maxwellian distribution in the input signal 102. The power penalty for small DGD values is small and may be negligible. The high DGD values generate significant power penalties. Additionally, the probability of a large DGD value is very small. Moreover, even if two channels both have a large DGD, the channels will be severely degraded only if the state-of-

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polarization of each channel is somewhat orthogonal to
its own PMD vector. Therefore, it is highly unlikely
that more than one channel will be severely degraded at
any given time.

5   [0025]   The compensation performance of the system 100
was demonstrated by operating on four equal-power WDM
channels with a channel spacing of about 4 nm. A multi-
section PMD emulator with rotatable connectors was used
to produce a Maxwellian-distributed DGD with a PMD-vector
10   autocorrelation function that closely resembles that of
real fiber. The average DGD produced by the PMD emulator
is about 42 ps. The PMD compensator 110 was implemented
with an electrically-controlled single-section
compensator which includes a polarization controller and
15   a short length of PM fiber to produce 30 ps of DGD. The
RF bandpass filter in the RF detector used for the
measurements had a bandwidth of about 4 GHz from 4GHz to
8GHz.

[0026]   FIGS. 3A and 3B show the power penalty
20   measurements for the combined four WDM channels by a
total of 1000 independent measurements with 250
measurements per channel. Each independent measurement
corresponds to a different emulator state. Simultaneous
compensation of all WDM channels can reduce the

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probability of the highly-degraded tail events. For the

combined WDM channels, the 2% worst case of the power

penalty distribution tail for the channels is reduced

from 9.6 dB to 5.3 dB.

5   [0027]   FIG. 4 shows one measurement of the eye diagram

of the four channels before and after compensation.

Channel 4, the most-degraded channel, is shown to improve

significantly after compensation without impacting the

other channels.

10   [0028]   FIG. 5 shows the simulated DGD distribution of

the worst channel in a four-channel WDM system with 25 ps

average DGD with and without compensation. Four

independent PMD vectors are simulated 200,000 times, and

the distribution of the maximum length (DGD) of the four

15   vectors is plotted as the DGD distribution for the worst

channel in the uncompensated system. For the compensated

system, a fixed 23-ps compensating PMD vector is used in

an optimum position on the Poincaré sphere for each

simulation to decrease the maximum length (DGD) PMD

20   vector. The simulation indicates that, the DGD

distribution of the worst channel has been improved on

average. In addition, the tail of the distribution has

been considerably reduced. The 0.01% tail of DGD

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distribution is reduced from 77 ps to 57 ps, which

reduces the power penalty from 9.5 dB to 4.3 dB.

[0029]   The PMD compensation system 100 in FIG. 1 may

be modified by having more than one pair of a

5   polarization controller 112 and a PM fiber 114. This

modification can be used to achieve additional freedom

and flexibility in adjusting or optimizing the direction

of the compensating PMD vector of the PMD compensator 110

on the Poincaré sphere and the length (DGD) of this

10   compensating vector and hence further improve the

compensation. FIG. 6 shows one PMD compensation system

600 with a PMD compensator 610 that has three adjustable

pairs of polarization controller and PM fibers, 110A,

110B, and 110C. The feedback control 136 produces three

15   control signals 136A, 136B, and 136 to control the three

different polarization controllers, respectively. In

general, as the number of the polarization controllers

and the PM fiber sections increases, it is more likely to

produce a resultant frequency-dependent PMD vector that

20   could better compensate in the PMD in each WDM channel.

[0030]   Although the present disclosure only includes a

few embodiments, other modifications and enhancements may

be made without departing from the following claims.

What Is Claimed Is:

1. A system, comprising:

a polarization-mode dispersion (PMD)
5 compensator operable to guide a plurality of wavelength-
division multiplexed (WDM) optical channels through a
common optical path to modify a differential group delay
(DGD) in each channel, said PMD compensator operable to
adjust said DGD in response to a control signal; and

10   a feedback control coupled to measure a
property of said channels as a whole and operable to
generate said control signal according to said property.

2. The system as in claim 1, wherein said property
15 includes an AC electrical power proportional to a current
or voltage that represents a total optical power of said
channels.

3. The system as in claim 2, wherein said feedback
20 control adjusts said PMD compensator to increase said AC
electrical power.

4. The system as in claim 1, wherein said PMD
compensator includes a polarization controller operable

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to adjust an output polarization in response to said

control signal, and a polarization-maintaining fiber.

5. The system as in claim 1, wherein said PMD

5   compensator includes a plurality of units connected in

series, each unit including a polarization controller

operable to adjust an output polarization in response to

said control signal and a polarization-maintaining fiber.

10   6. The system as in claim 1, wherein said feedback

control includes:

an optical coupler disposed to couple a portion

of an output signal from said PMD compensator that

combines said channels;

15   an optical detector to convert said portion

into an electrical signal;

an electrical power detector to detect an AC

power of said electrical signal; and

a control circuit to generate said control

20   signal to increase said AC power.

7. The system as in claim 6, wherein said electrical

power detector includes an electrical bandpass filter to

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select said AC power in a frequency band to increase

response sensibility of said feedback control.

        8. The system as in claim 6, wherein said electrical

5   power detector includes at least two electrical bandpass

filters with different frequency bands to select said AC

power in one of said frequency bands to increase response

sensibility of said feedback control.

10   9. A method, comprising:

        directing each of a plurality of wavelength-

division multiplexed (WDM) optical channels through a

common optical path to modify a differential group delay

(DGD) in each channel so as to produce an output with

15   modified WDM channels;

        measuring power of an AC portion of said

output; and

        modifying the DGD to increase said power.

20   10. The method as in claim 9, wherein said

modification includes adjusting a polarization of each

channel relative to a principal axis of a polarization-

maintaining fiber in said common optical path.

11. The method as in claim 9, further comprising:

      filtering said power in frequency to select a

portion of said power in a selected frequency band; and

      wherein the DGD is modified to increase said

5   portion in said selected frequency band.

12. The method as in claim 9, further comprising:

      filtering said power in frequency to select a

first portion of said power in a first selected frequency

10 band;

      filtering said power in frequency to select a

second portion of said power in a second selected

frequency band; and

      selecting one of said first and said portions

15 to be increased by modifying the DGD.

13. The method as in claim 9, wherein said measuring

power of said AC portion of said output includes:

      tapping an output of said common optical path

20 to produce an optical monitor signal;

      converting said optical monitor signal into an

electrical signal;

      measuring an AC electrical power of said

electrical signal; and

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filtering said AC electrical power in frequency
to produce said AC portion.

14. The method as in claim 9, wherein said common

5   optical path includes a first optical polarization
controller and a first polarization-maintaining fiber,
and wherein said first optical polarization controller is
adjusted to modify the DGD.

10   15. The method as in Claim 9, wherein said common
optical path includes a plurality of pairs of a
polarization controller and a polarization-maintaining
fiber connected in series, wherein each optical
polarization controller is adjusted to modify the DGD.

15

16. A system, comprising:

a polarization-mode dispersion (PMD)
compensator operable to guide a plurality of wavelength-
division multiplexed (WDM) optical channels through a

20   common optical path to modify a differential group delay
(DGD) in each channel, said common optical path
comprising a plurality of adjustable units connected in
series respectively operable to adjust the DGD in

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response to a plurality of control signals, respectively;
and

a feedback control coupled to measure a
property of said channels as a whole after transmitting

5   through said common optical path and operable to generate
said control signals according to said property.

17. The system as in claim 16, wherein each
adjustable unit includes a polarization controller

10   operable to adjust an output polarization in response to
a respective control signal and a polarization-
maintaining fiber.

18. The system as in claim 16, wherein said feedback

15   control includes:

an optical coupler disposed to couple a portion
of an output signal from said PMD compensator that
combines said channels;

an optical detector to convert said portion

20   into an electrical signal;

an electrical power detector to detect an AC
power of said electrical signal; and

a control circuit to generate said control
signals to increase said AC power.

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19. A method, comprising:

directing each of a plurality of wavelength-division multiplexed (WDM) optical channels through a

5   common optical path to modify a differential group delay (DGD) in each channel so as to produce an output with modified WDM channels; and

controlling said DGD to reduce an overall signal fading in said output caused by polarization-mode

10   dispersion (PMD) on all of said channels without separately compensating PMD in each channel.

20. The method as in claim 19, further comprising:

measuring power of an AC portion of said

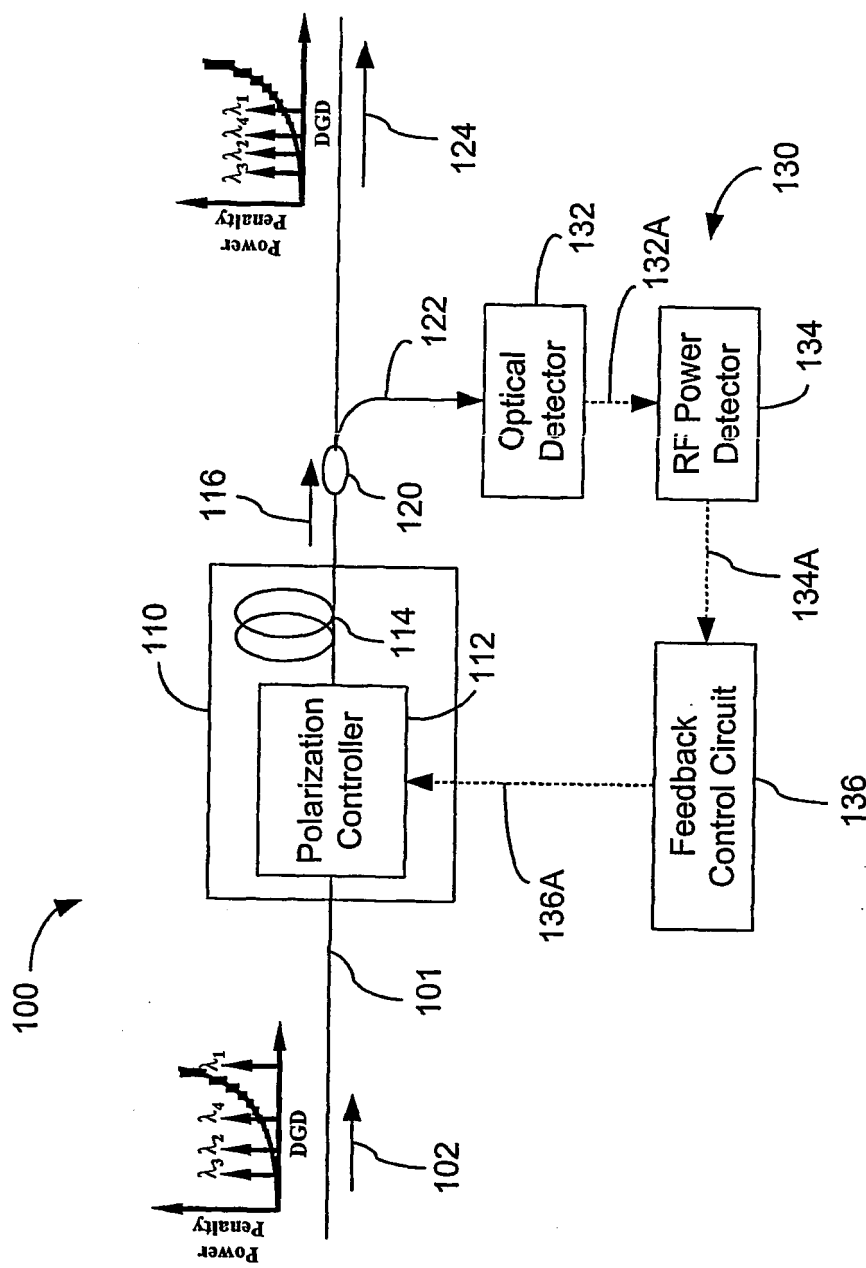15   output; and

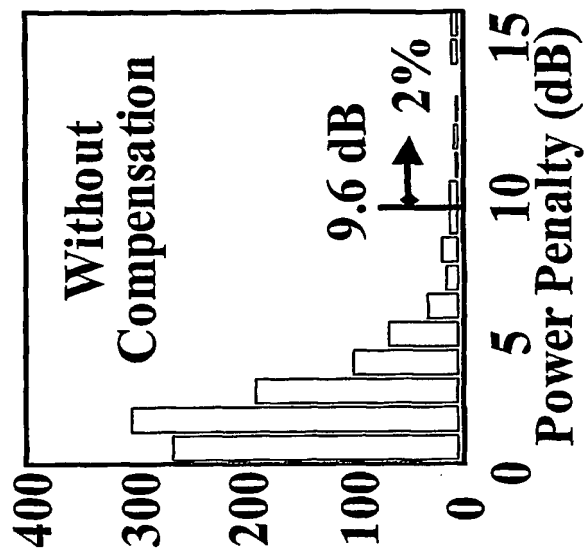modifying the DGD to increase said power.
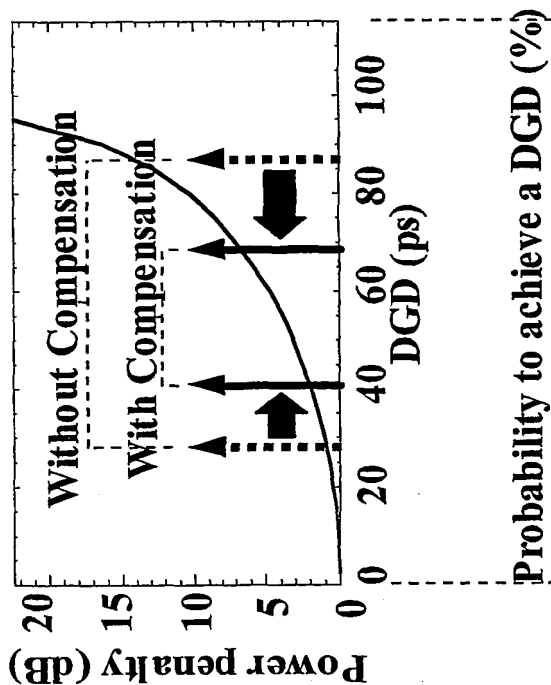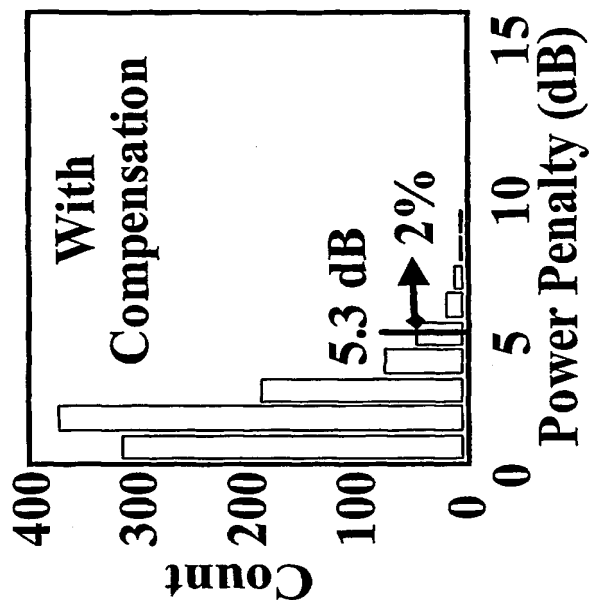
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FIG. 1

FIG. 3A

FIG. 3B

FIG. 2A

FIG. 2B

FIG. 4

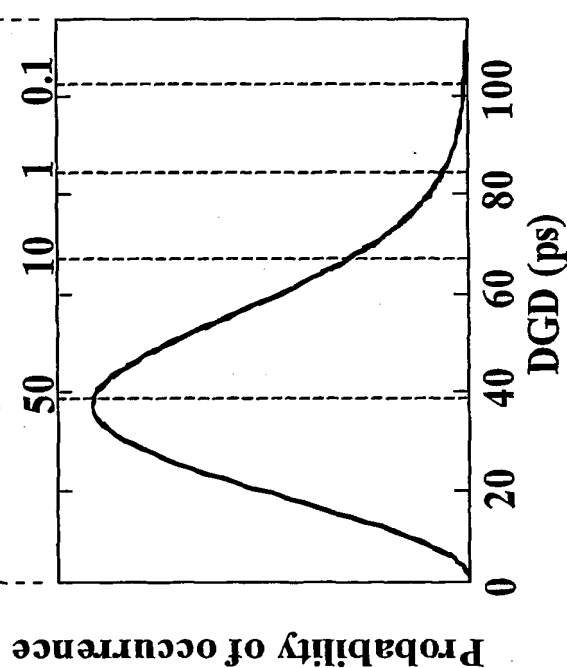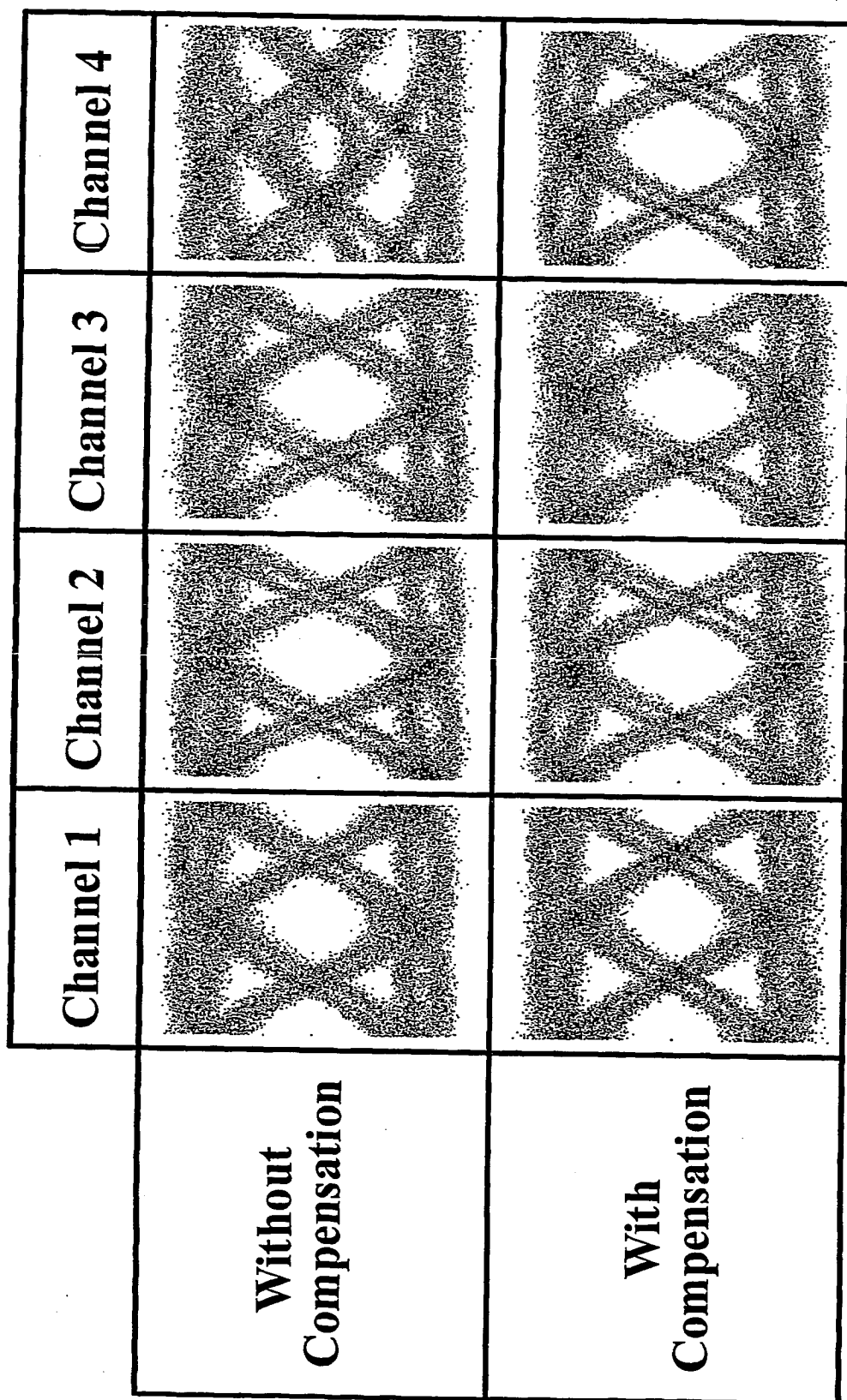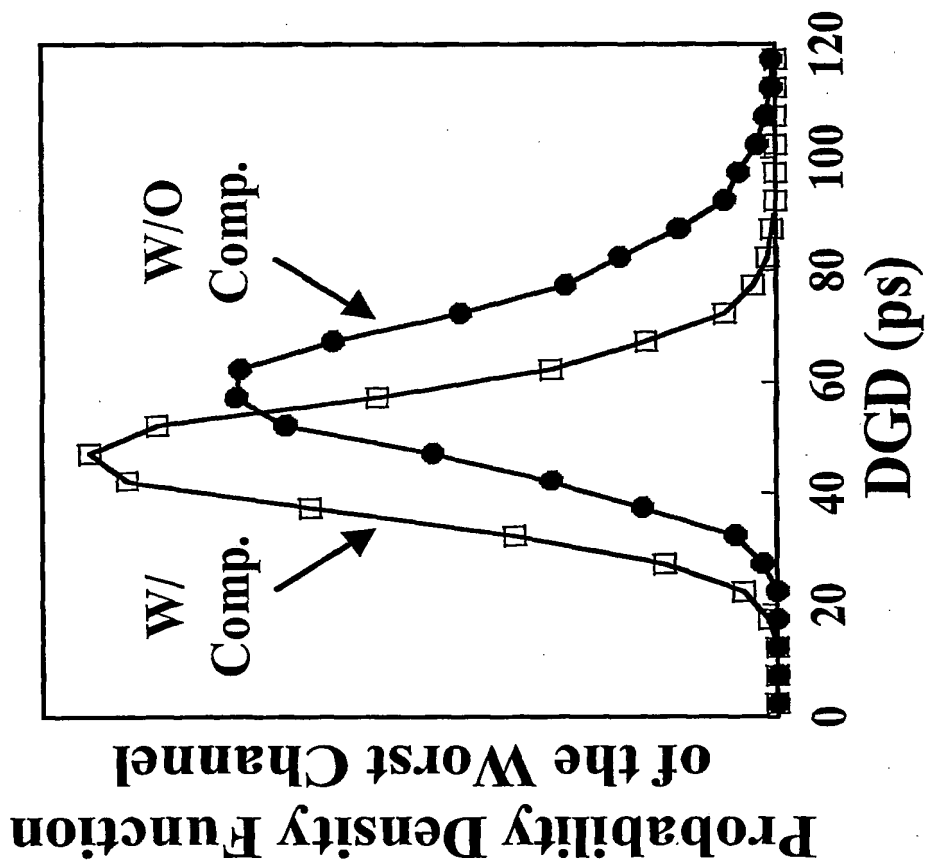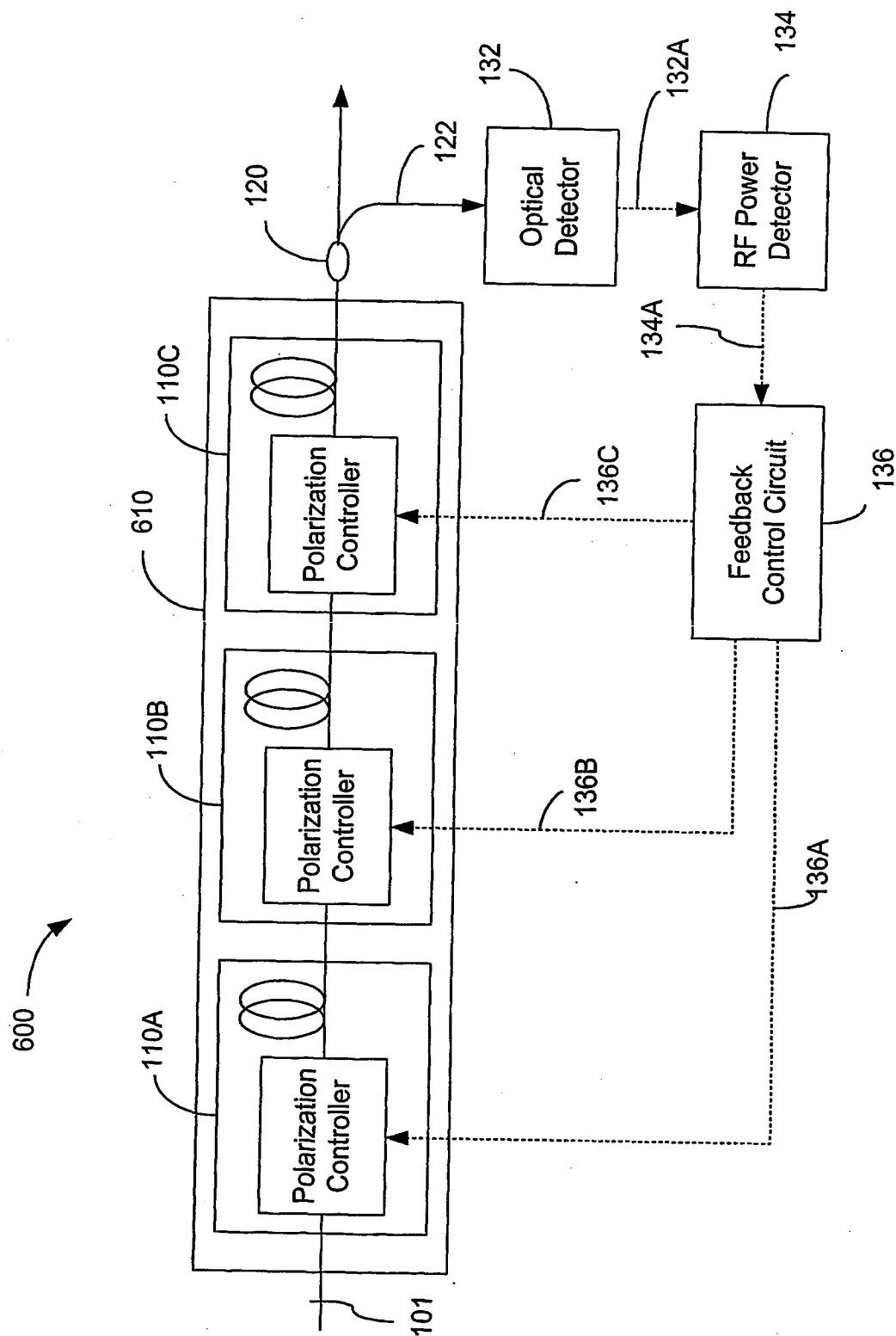|	Channel 1	Channel 2	Channel 3	Channel 4
Without Compensation				
With Compensation				

FIG. 5

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US01/07257

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :H04B 10/00; G02B 6/00; H04J 14/08
US CL :359/161, 122, 156, 110, 140; 385/11, 24, 27, 28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/161, 122, 156, 110, 140; 385/11, 24, 27, 28

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EAST
search terms: polarization mode dispension, differential group delay, feedback

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	US 5,930,414 A (FISHMAN et al.) 27 July 1999, figure 1, col. 5, lines 33-37, figure 2, col. 7, line 25, col. 7, lines 50-51, col. 6, line 66- col. 7, line 14.	1-3, 6-7, 9, 11, 13, 16, 18-20 ------------ 4, 5, 8, 10, 12, 14, 15, 17
Y	US 5,473,457 A (ONO) 05 December 1995, figure 1, col. 3, lines 41-42	4, 5, 10, 14, 15, 17
Y	US 5,949,560 A (ROBERTS et al.) 07 September 1999, figures 4, 6 and 13.	8, 12

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
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"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
		"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 MAY 2001	16 JUL 2001

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Form PCT/ISA/210 (second sheet) (July 1998)★

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(51) International Patent Classification⁷: **H04B 10/00**, G02B 6/00, H04J 14/08

(21) International Application Number: PCT/US01/07257

(22) International Filing Date: 6 March 2001 (06.03.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
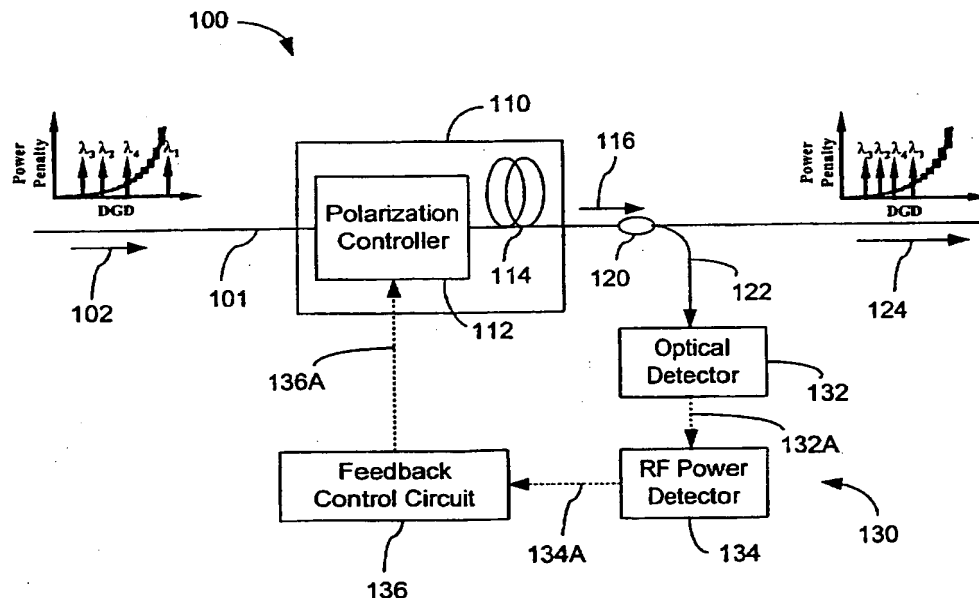60/187,126　　6 March 2000 (06.03.2000)　US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US　　　　60/187,126 (CON)
Filed on　　6 March 2000 (06.03.2000)

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(81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX,

(54) Title: COMPENSATION FOR POLARIZATION-MODE DISPERSION IN MULTIPLE WAVELENGTH-DIVISION MULTIPLEXED CHANNELS

(57) Abstract: Techniques for compensating for polarization-mode dispersion (PMD) in multiple wavelength-division multiplexed (WDM) channels (102) by processing all WDM channels in the same manner without demultiplexing the channels. A feedback control (136) is provided to decrease the worst-case power penalty and the channel fading probability by optimizing over the entire group of WDM channels.

MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) **Designated States** *(regional):* ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(48) **Date of publication of this corrected version:**

1 November 2001

(15) **Information about Correction:**
see PCT Gazette No. 44/2001 of 1 November 2001, Section II

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.